10. Replication

CSEP 545 Transaction Processing
Philip A. Bernstein
Sameh Elnikety

Outline

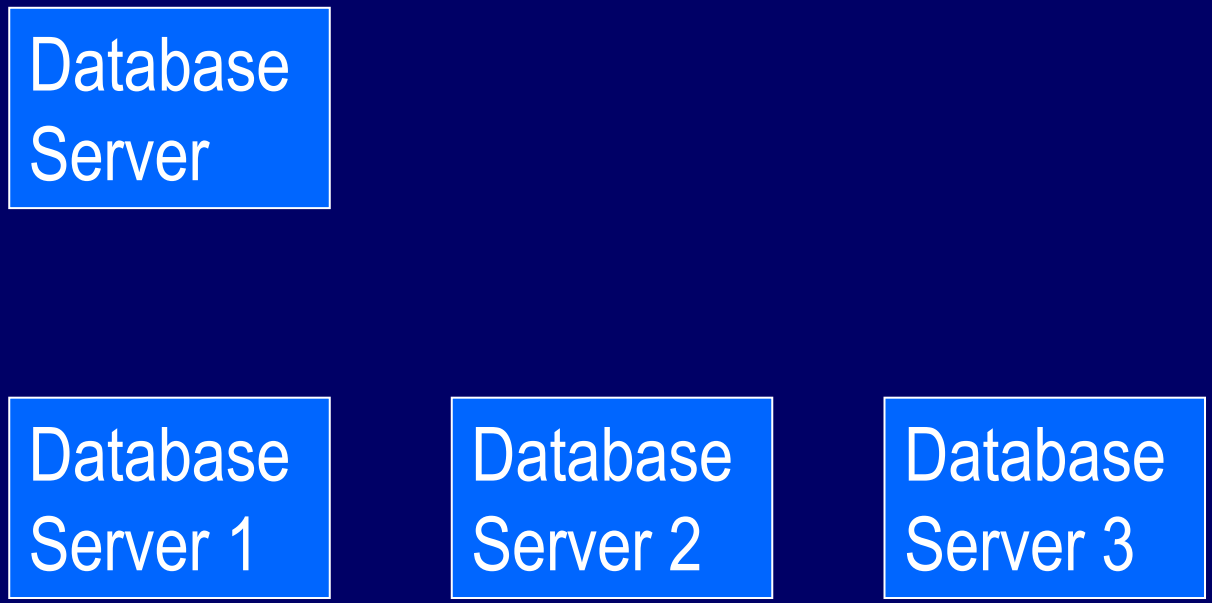
1. Introduction
2. Primary-Copy Replication
3. Multi-Master Replication
4. Other Approaches
5. Products

1. Introduction

- Replication - using multiple copies of a server or resource for better availability and performance.
  - Replica and Copy are synonyms

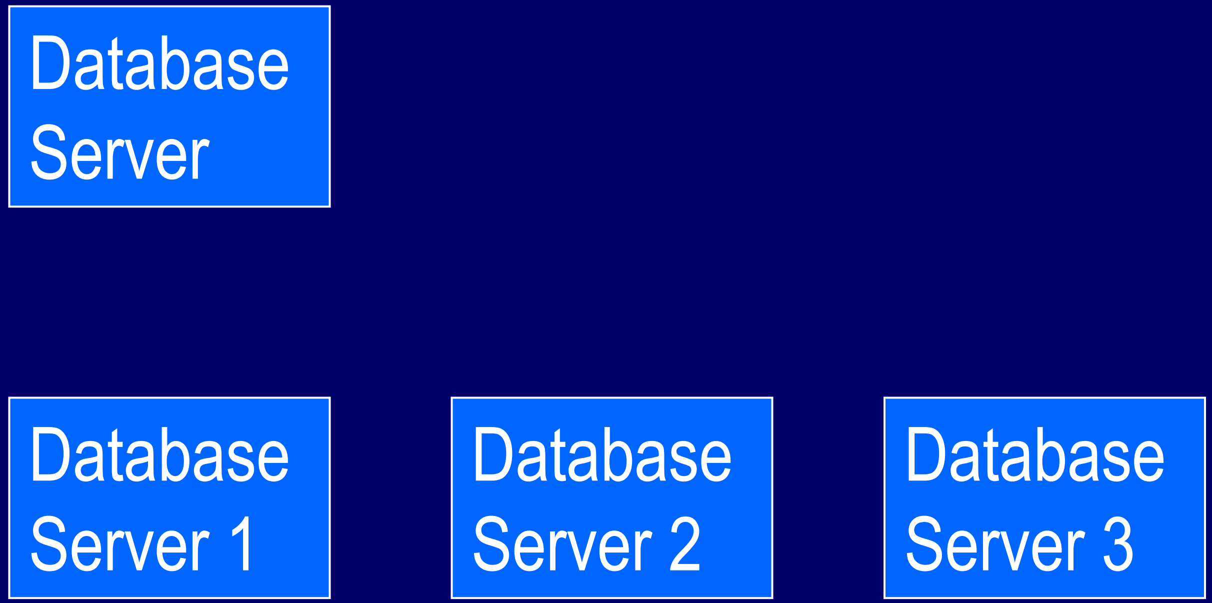
- If you're not careful, replication can lead to
  - worse performance - updates must be applied to all replicas and synchronized
  - worse availability - some algorithms require multiple replicas to be operational for any of them to be used

Read-only Database



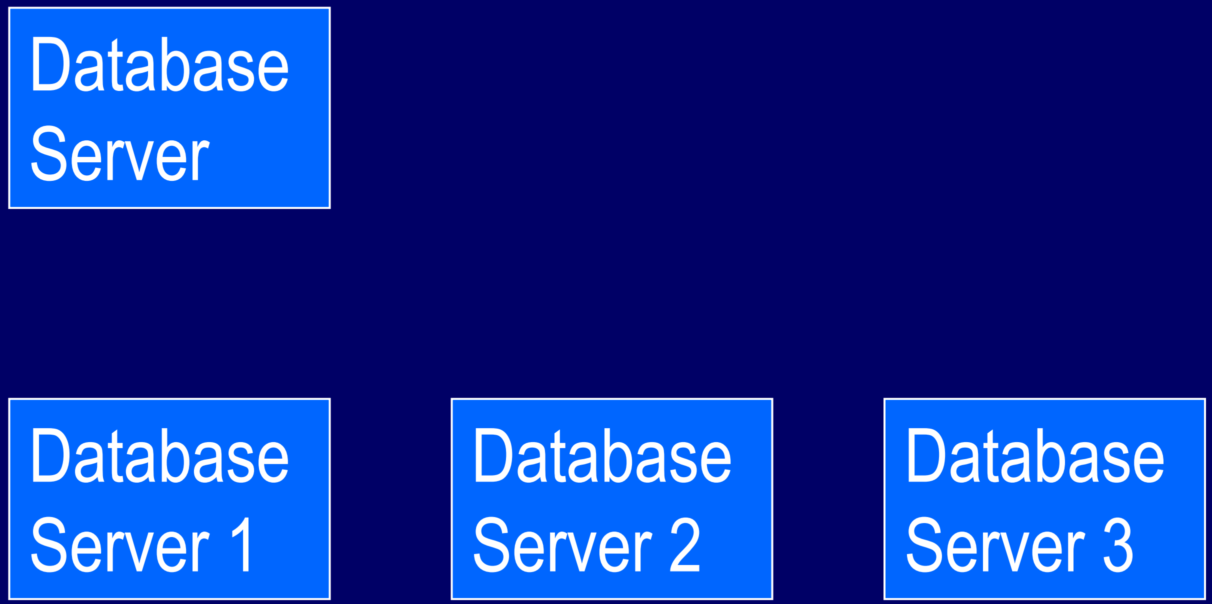
- $T_1 = \{\ r[x]\ \}$

Update-only Database



- $T_1 = \{ w[x=1] \}$
- $T_2 = \{ w[x=2] \}$

Update-only Database



- $T_1 = \{\ w[x=1]\ \}$
- $T_2 = \{\ w[y=1]\ \}$

Replicated Database

Database Server 1

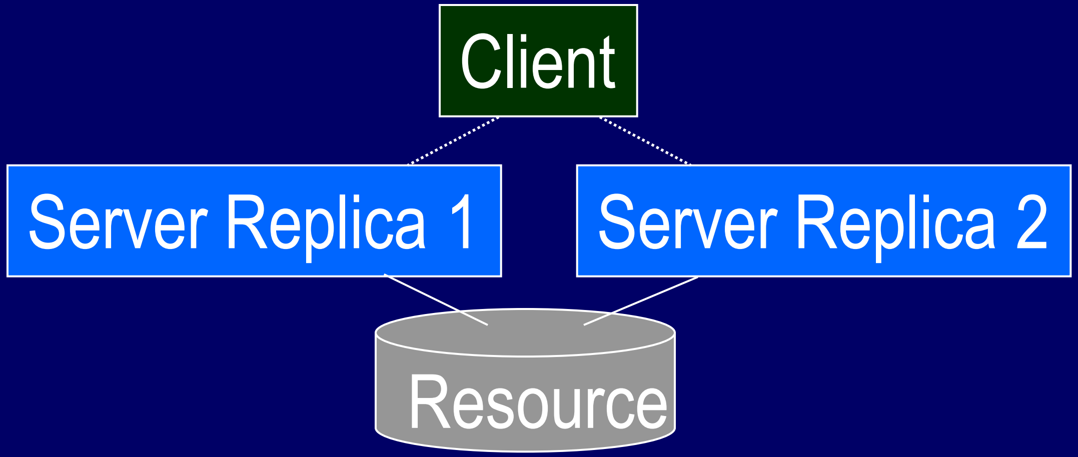
Database Server 2

Database Server 3

- Objective
  - Availability
  - Performance
- Transparency
  - 1 copy serializability
- Challenge
  - Propagating and synchronizing updates

Replicated Server

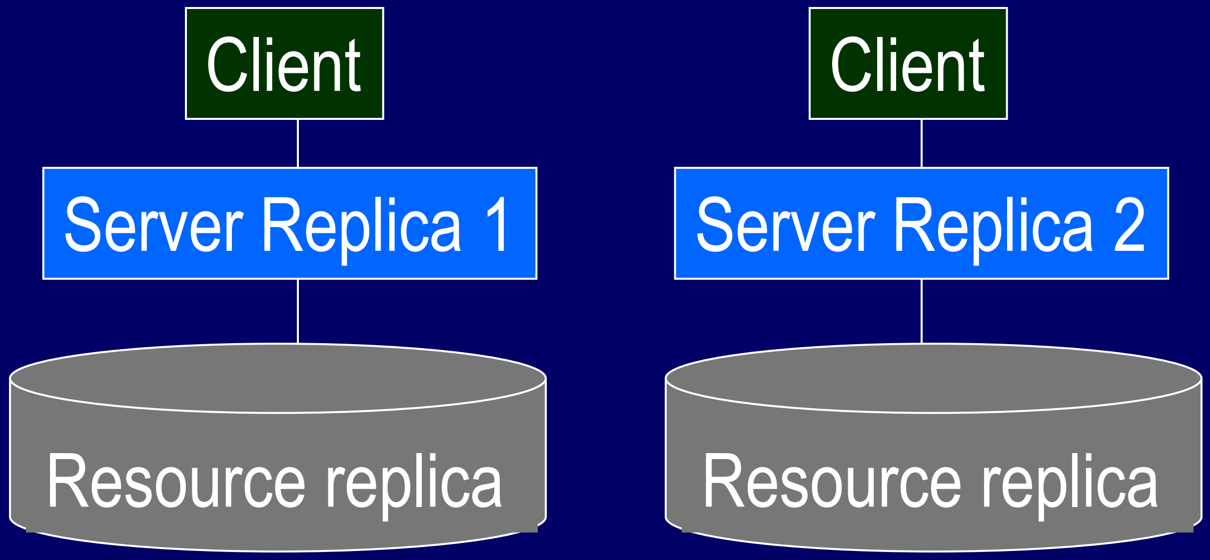
- Can replicate servers on a common resource
  - Data sharing - DB servers communicate with shared disk



- Helps availability for process (not resource) failure
- Requires a replica cache coherence mechanism, so this helps performance only if
  - little conflict between transactions at different servers or
  - loose coherence guarantees (e.g. read committed)

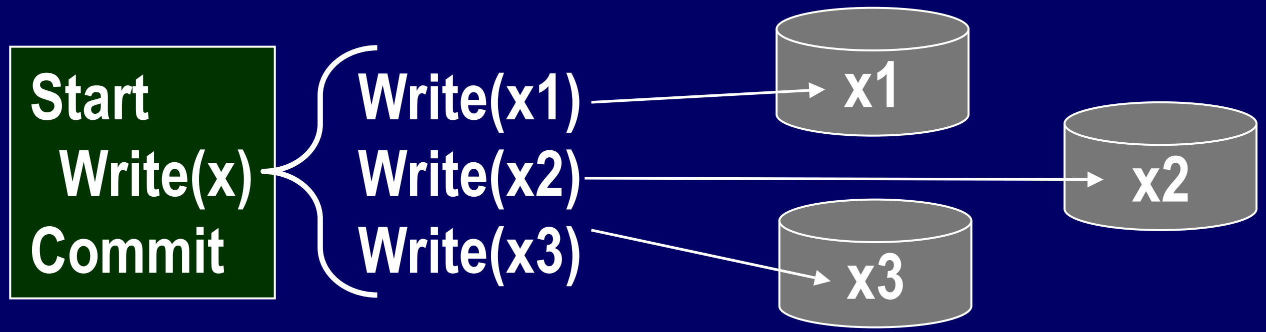
Replicated Resource

- To get more improvement in availability, replicate the resources (too)
- Also increases potential throughput
- This is what's usually meant by replication
- It's the scenario we'll focus on



Synchronous Replication

- Replicas function just like a non-replicated resource
  - Txn writes data item x. System writes all replicas of x.
  - Synchronous – replicas are written within the update txn
  - Asynchronous – One replica is updated immediately. Other replicas are updated later



- Problems with synchronous replication
  - Too expensive for most applications, due to heavy distributed transaction load (2-phase commit)
  - Can’t control when updates are applied to replicas

Synchronous Replication - Issues

- If you just use transactions, availability suffers.
- For high-availability, the algorithms are complex and expensive, because they require heavy-duty synchronization of <u>failures</u>.
- … of failures? How do you synchronize failures?
- Assume replicas x_A, x_B of x and y_C, y_D of y

$$
\begin{tikzcd}
r_1[x_A] \arrow[r] \arrow[dr] & y_D \text{ fails} \arrow[r] & w_1[y_C] \\
r_2[y_D] \arrow[r] \arrow[ur] & x_A \text{ fails} \arrow[r] & w_2[x_B]
\end{tikzcd}
$$

Not equivalent to a one-copy execution, even if x_A and y_D never recover!

- DBMS products support it only in special situations

Atomicity & Isolation Goal

- One-copy serializability (abbr. *1SR*)
  - An execution of transactions on the replicated database has the same effect as a serial execution on a one-copy database.
- *Readset* (resp. *writeset*) - the set of data items (not copies) that a transaction reads (resp. writes).
- 1SR Intuition: the execution is SR *and* in an equivalent serial execution, for each txn T and each data item x in readset(T), T reads from the most recent txn that wrote into <u>any</u> copy of x.
- To check for 1SR, first check for SR (using SG), then see if there's equivalent serial history with the above property

Atomicity & Isolation (cont'd)

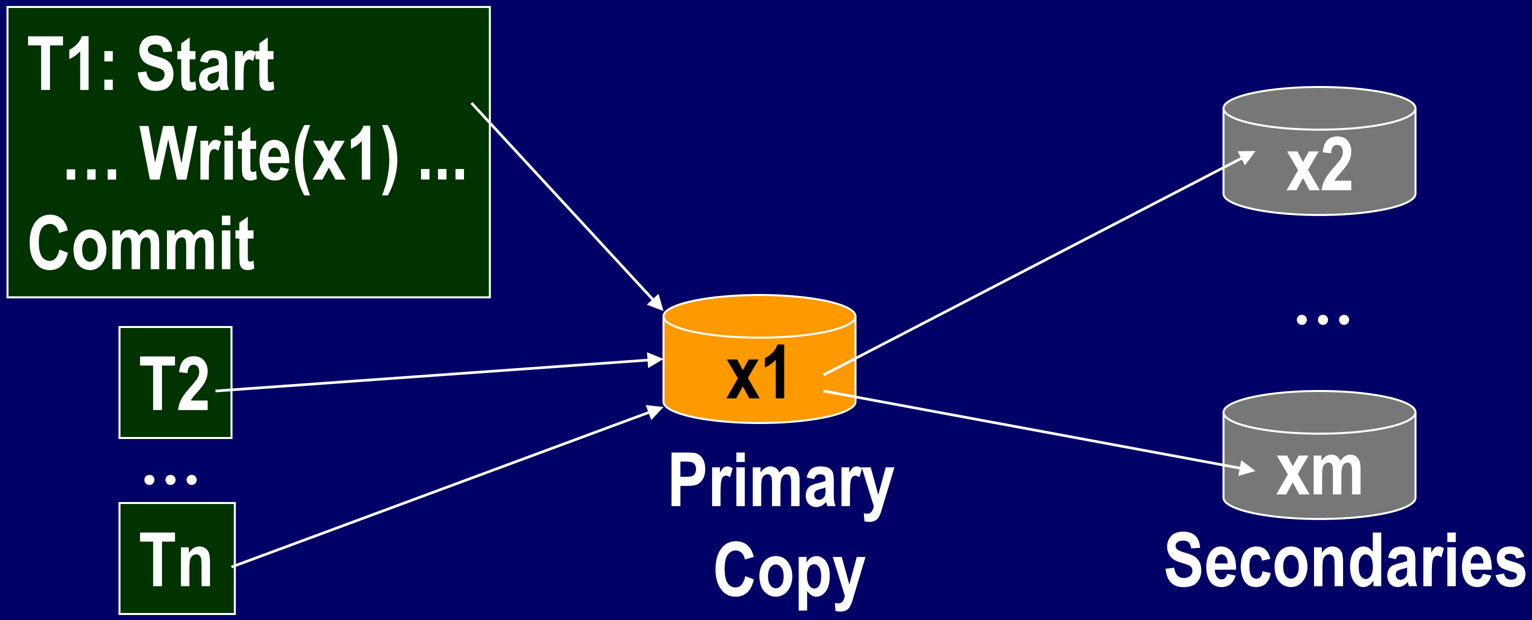
- Previous example was not 1SR. It is equivalent to
  - $r_1[x_A]$ $\mathbf{w_1[y_C]}$ $\mathbf{r_2[y_D]}$ $w_2[x_B]$ and
  - $r_2[y_D]$ $\mathbf{w_2[x_B]}$ $\mathbf{r_1[x_A]}$ $w_1[y_C]$
  - but in both cases, the second transaction does not read its input from the previous transaction that wrote that input.
- These are 1SR
  - $r_1[x_A]$ $w_1[\mathbf{y_D}]$ $r_2[y_D]$ $w_2[x_B]$
  - $r_1[x_A]$ $w_1[y_C]$ $\mathbf{w_1[y_D]}$ $r_2[y_D]$ $w_2[x_A]$ $w_2[x_B]$
- The previous history is the one you would expect
  - Each transaction reads one copy of its readset and writes into all copies of its writeset
- But it may not always be feasible, because some copies may be unavailable.

Asynchronous Replication

- Asynchronous replication
  - Each transaction updates one replica.
  - Updates are propagated later to other replicas.
- Primary copy: Each data item has a primary copy
  - All transactions update the primary copy
  - Other copies are for queries and failure handling
- Multi-master: Transactions update different copies
  - Useful for disconnected operation, partitioned network
- Both approaches ensure that
  - Updates propagate to all replicas
  - If new updates stop, replicas converge to the same state
- Primary copy ensures serializability, and often 1SR
  - Multi-master does not.

2. Primary-Copy Replication

- Designate one replica as the primary copy (publisher)
- Transactions may update only the primary copy
- Updates to the primary are sent later to secondary replicas (subscribers) in the order they were applied to the primary



Update Propagation

- Collect updates at the primary using triggers or by post-processing the log
  - Triggers: on every update at the primary, a trigger fires to store the update in the update propagation table.
  - Log post-processing: "sniff" the log to generate update propagations
- Log post-processing (log sniffing)
  - Saves triggered update overhead during on-line txn.
  - But R/W log synchronization has a (small) cost
- Optionally identify updated fields to compress log
- Most DB systems support this today.

Update Processing 1/2

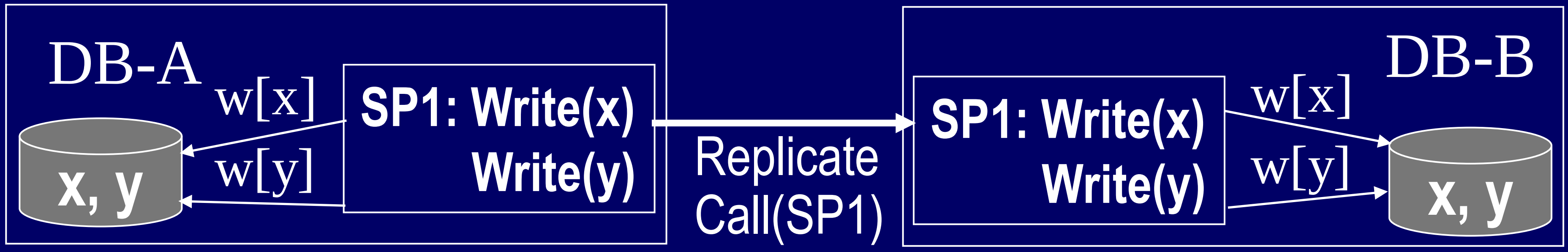
- At the replica, for each tx T in the propagation stream, execute a refresh tx that applies T's updates to replica.
- Process the stream serially
  - Otherwise, conflicting transactions may run in a different order at the replica than at the primary.
  - Suppose log contains $w_1[x]\ c_1\ w_2[x]\ c_2$. Obviously, T_1 must run before T_2 at the replica.
  - So the execution of update transactions is serial.
- Optimizations
  - Batching: {w(x)} {w(y)} -> {w(x), w(y)}
  - "Concurrent" execution

Update Processing 2/2

- To get a 1SR execution at the replica
  - Refresh transactions and read-only queries use an atomic and isolated mechanism (e.g., 2PL)
- Why this works
  - The execution is serializable
  - Each state in the serial execution is one that occurred at the primary copy
  - Each query reads one of those states
- Client view
  - Session consistency

Request Propagation

- An alternative to propagating updates is to propagate procedure calls (e.g., a DB stored procedure call).



- Or propagate requests (e.g. txn-bracketed stored proc calls)
- Requirements
  - Must ensure same order at primary and replicas
  - Determinism
- This is often a txn middleware (not DB) feature.

Failure & Recovery Handling 1/3

- Secondary failure - nothing to do till it recovers
  - At recovery, apply the updates it missed while down
  - Needs to determine which updates it missed, just like non-replicated log-based recovery
  - If down for too long, may be faster to get a whole copy
- Primary failure
  - Normally, secondaries wait till the primary recovers
  - Can get higher availability by electing a new primary
  - A secondary that detects primary's failure starts a new election by broadcasting its unique replica identifier
  - Other secondaries reply with their replica identifier
  - The largest replica identifier wins

Failure & Recovery Handling 2/3

- Primary failure (cont'd)
  - All replicas must now check that they have the same updates from the failed primary
  - During the election, each replica reports the id of the last log record it received from the primary
  - The most up-to-date replica sends its latest updates to (at least) the new primary.

Failure & Recovery Handling 3/3

- Primary failure (cont'd)
  - Lost updates
  - Could still lose an update that committed at the primary and wasn't forwarded before the primary failed … but solving it requires synchronous replication (2-phase commit to propagate updates to replicas)
  - One primary and one backup
    - There is always a window for lost updates.

Communications Failures

- Secondaries can’t distinguish a primary failure from a communication failure that partitions the network.
- If the secondaries elect a new primary and the old primary is still running, there will be a reconciliation problem when they’re reunited. This is multi-master.
- To avoid this, one partition must know it’s the only one that can operate. It can’t communicate with other partitions to figure this out.
- Could make a static decision.
  E.g., the partition that has the primary wins.
- Dynamic solutions are based on Majority Consensus

Majority Consensus

- Whenever a set of communicating replicas detects a replica failure or recovery, they test if they have a majority (more than half) of the replicas.
- If so, they can elect a primary
- Only one set of replicas can have a majority.
- Doesn’t work with an even number of copies.
  – Useless with 2 copies
- Quorum consensus
  – Give a weight to each replica
  – The replica set that has a majority of the weight wins
  – E.g. 2 replicas, one has weight 1, the other weight 2

3. Multi-Master Replication

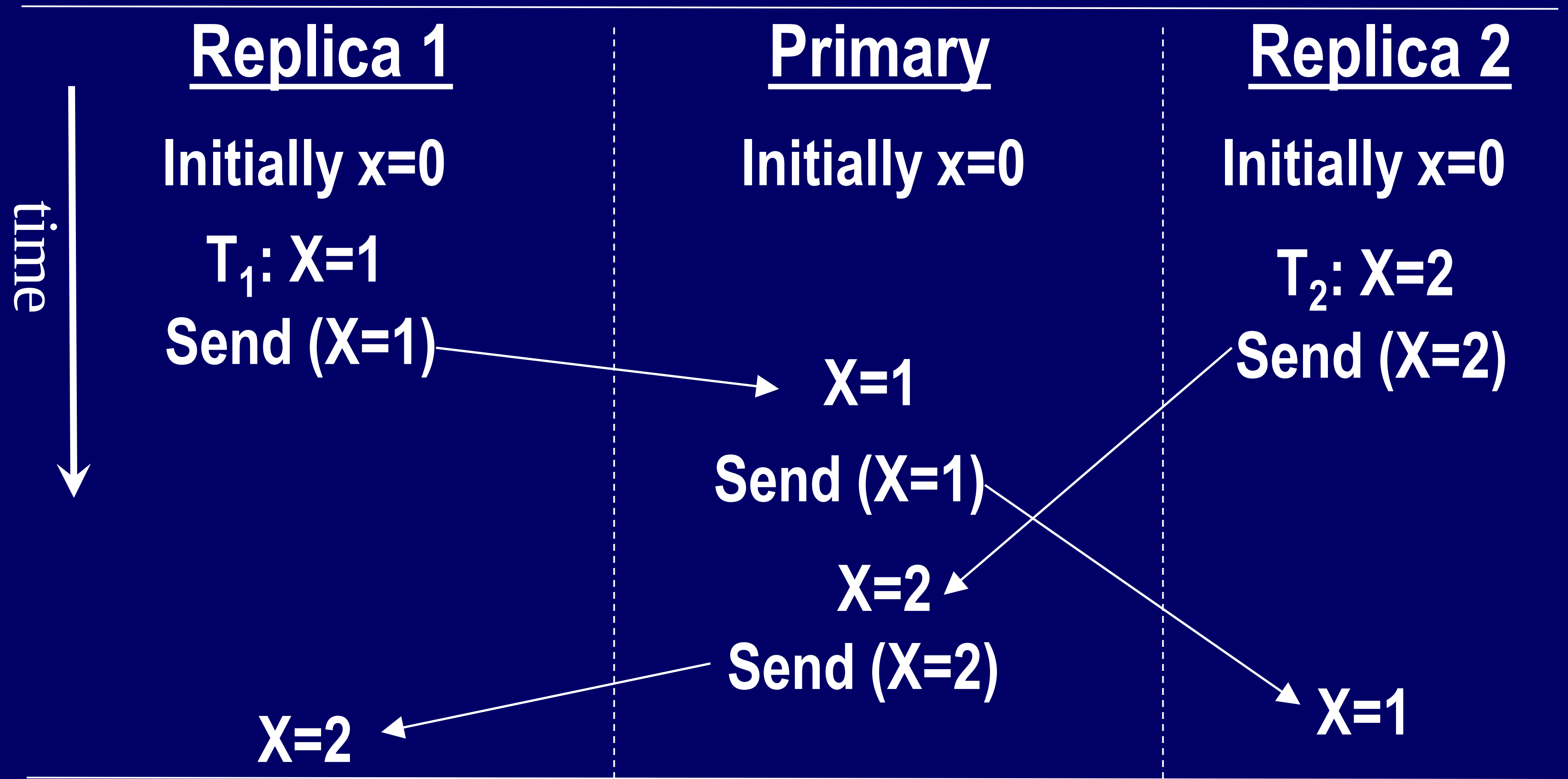
- Some systems <u>must</u> operate when partitioned.
  - Requires many updatable copies, not just one primary
  - Conflicting updates on different copies are detected late
- Classic example - salesperson's disconnected laptop

  Customer table (rarely updated)　　　Orders table (insert mostly)

  Customer log table (append only)
  - So conflicting updates from different salespeople are rare
- Use primary-copy algorithm, with multiple masters
  - Each master exchanges updates ("gossips") with other replicas when it reconnects to the network
  - Conflicting updates require reconciliation (i.e. merging)
- In Lotus Notes, Access, SQL Server, Oracle, …

Example of Conflicting Updates

- Assume all updates propagate via the primary



- Replicas end up in different states

Thomas’ Write Rule

- To ensure replicas end up in the same state
  - Tag each data item with a timestamp
  - A transaction updates the value and timestamp of data items (timestamps monotonically increase)
  - An update to a replica is applied only if the update’s timestamp is greater than the data item’s timestamp
  - You only need timestamps of data items that were recently updated (where an older update could still be floating around the system)
- All multi-master products use some variation of this
- Robert Thomas, *ACM TODS*, June ’79

Thomas Write Rule $\not\Rightarrow$ Serializability

Replica 1	Primary	Replica 2
T_1: read x=0 (TS=0)	Initially x=0,TS=0	T_1: read x=0 (TS=0)
T_1: X=1, TS=1		T_2: X=2, TS=2
Send (X=1, TS=1)	X=1, TS=1	Send (X=2, TS=2)
	Send (X=1, TS=1)	
	X=2, TS=2	
	Send (X=2, TS=2)	
X=2, TS=2		~~X=1, TS=1~~

- Replicas end in the same state, but neither T_1 nor T_2 reads the other's output, so the execution isn't serializable.
- This requires reconciliation

Multi-Master Performance

- The longer a replica is disconnected and performing updates, the more likely it will need reconciliation
- The amount of propagation activity increases with more replicas
  - If each replica is performing updates, the effect is quadratic in the number of replicas

Making Multi-Master Work

- Transactions
  - T_1: x++ {x=1} at replica 1
  - T_2: x++ {x=1} at replica 2
  - T_3: x++ {y=1} at replica 3
  - Replica 2 and 3 already exchanged updates
- On replica 1
  - Current state { x=1, y=0 }
  - Receive update from replica 2 {x=1, y=1}
  - Receive update from replica 3 {x=1, y=1}

Making Multi-Master Work

- Time in a distributed system
  - Emulate global clock
  - Use local clock
  - Logical clock
  - Vector clock
- Dependency tracking metadata
  - Per data item
  - Per replica
  - This could be bigger than the data

Microsoft Access and SQL Server

- Each row R of a table has 4 additional columns
  - Globally unique id (GUID)
  - Generation number, to determine which updates from other replicas have been applied
  - Version num = the number of updates to R
  - Array of [replica, version num] pairs, identifying the largest version num it got for R from every other replica
- Uses Thomas' write rule, based on version nums
  - Access uses replica id to break ties.
  - SQL Server 7 uses subscriber priority or custom conflict resolution.

4. Other Approaches (1/2)

- Non-transactional replication using timestamped updates and variations of Thomas' write rule
  - Directory services are managed this way
- Quorum consensus per-transaction
  - Read and write a quorum of copies
  - Each data item has a version number and timestamp
  - Each read chooses a replica with largest version number
  - Each write increments version number one greater than any one it has seen
  - No special work needed for a failure or recovery

Other Approaches 2/2

- Read-one replica, write-all-available replicas
  - Requires careful management of failures and recoveries
- E.g., Virtual partition algorithm
  - Each node knows the nodes it can communicate with, called its view
  - Txn T can execute if its home node has a view including a quorum of T's readset and writeset
  - If a node fails or recovers, run a view formation protocol (much like an election protocol)
  - For each data item with a read quorum, read the latest version and update the others with smaller version #.

Summary

- State-of-the-art products have rich functionality.
  - It’s a complicated world for app designers
  - Lots of options to choose from
- Most failover stories are weak
  - Fine for data warehousing
  - For 24×7 TP, need better integration with cluster node failover